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Constraining axion by polarized prompt emission from gamma ray bursts

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Abstract

A polarized gamma ray emission spread over a sufficiently wide energy band from a strongly magnetized astrophysical object like gamma ray bursts (GRBs) offers an opportunity to test the hypothesis of invisible axion. The axionic induced dichroism of gamma rays at different energies should cause a misalignment of the polarization plane for higher energy events relative to that one for lower energies events resulting in the loss of statistics needed to form a pattern of the polarization signal to be recognized in a detector. According to this, any evidence of polarized gamma rays coming from an object with extended magnetic field could be interpreted as a constraint on the existence of the invisible axion for a certain parameter range. Based on reports of polarized MeV emission detected in several GRBs we derive a constraint on the axion-photon coupling. This constraint $g_{a\gamma\gamma} \leq 2.2 \cdot 10^{-11}$ GeV^{-1} calculated for the axion mass $m_a = 10^{-3}$ eV is competitive with the sensitivity of CAST and becomes even stronger for lower masses.

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The Peccei-Quinn (PQ) mechanism [1] remains perhaps the most natural solution to the CP problem in QCD. A new chiral $U_{PQ}(1)$ symmetry being spontaneously broken at some large energy scale, f_a, and explicitly broken by the color anomaly at QCD scale would allow for the dynamical vanishing of the θ term and thus the restoration of the CP symmetry in strong interactions. The pseudo-scalar field, which drives the relaxation of the θ term to zero is called axion. The most important phenomenological property of this axion is its two-photon vertex interaction, which allows for axion to photon conversion in the presence of an external electromagnetic and magnetic fields [2] through an interaction term

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} a, \tag{1}$$

where a is the axion field, F is the electromagnetic field strength tensor, $\tilde{F}$ its dual, $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic fields respectively. The axion-photon coupling strength is quantified by

$$g_{a\gamma\gamma} = \xi \frac{\alpha}{2\pi} \frac{1}{f_a}, \tag{2}$$

where α is the fine-structure constant and ξ is an order one [1] parameter which depends on the details of the electromagnetic and color anomalies of the axial current associated with axion field. For review of the properties of the invisible axion as well as various types of constraints on the axion mass and couplings see [3, 4].

According to [7] the axion-photon mixing (1) gives rise to vacuum birefringence and dichroism, which are qualitatively identical to those arising from the QED magnetized vacuum. If one considers a beam of laying polarized monochromatic photons with frequency ω and wave vector $\mathbf{k}$ propagating in a vacuo along in a uniform magnetic field $\mathbf{B}$ laing at a nonvanishing angle ϕ with the wave vector, due to the birefringence the beam polarization becomes elliptical at some distance from the source. On the other hand, the dichroism produces a rotation of the ellipse's major axis with respect to the initial polarization. In this letter we only consider the axionic dichroism induced rotation angle ϵ of the polarization plane of an initially linearly polarized monochromatic beam given in [7, 8]:

$$\epsilon = N \frac{g_{a\gamma\gamma}^2 B^2 \omega^2}{m_a^2} \sin^2\left(\frac{m_a^2 L}{4\omega}\right) \sin 2\phi, \tag{3}$$

where m_a is the mass of the axion, L is the length of the magnetized region, N is the number of passes through the cavity with the magnetic field if for instance a laser experiment like PVLAS [9, 10] is considered. The validity of the approximation (3) is provided if the oscillation wavenumber

$$\Delta_{\rm osc}^2 = \left(\frac{m_a^2 - \omega_{\rm pl}}{2\omega}\right)^2 + B^2 g_{a\gamma\gamma}^2 \tag{4}$$

is dominated by the axion mass term. In fact, (4) pertains to the situation in which the beam propagates in a magnetized plasma, which gives rise to an effective photon mass

[1]Two quite distinct invisible axion models, namely the KSVZ [5] (hadronic axion) and the DFSZ [6] one, lead to quite similar $g_{a\gamma\gamma}$.

set by the plasma frequency $\omega_{\rm pl} = \sqrt{4\pi\alpha n_e/m_e} \simeq 3.7 \cdot 10^{-11}\sqrt{n_e/{\rm cm}^{-3}}$ eV, where n_e is the electron density and m_e is the electron mass. Since the dichroism rotation, expected to arise in the QED vacuum, and is suppressed with respect to birefringence by factor $(B/B_{cr})^2$ [11], where $B_{cr} = m_e/e \simeq 4.4 \cdot 10^{13}$G, any observable rotation in vacuum should be attributed to the axion-photon mixing term (1).

The polarization of the prompt gamma ray emission has been measured in four bright GRBs: GRB021206, GRB930131, GRB960924 and GRB041219a. The first measurements made in [12] with Ranaty High Energy Solar Spectrometer Imager (RHESSI) satellite [13], found a linear polarization, $\Pi = (80 \pm 20)\%$, of the gamma rays from GRB021206 across the spectral window 0.15-2 MeV. The analysis techniques have been challenged in [14] and defended in [15]. Subsequent analyses made in [16] confirmed the results of [12] but at the lower level of significance. Later, in [17] the BATSE instrument on board of the Compton Gamma Ray Observatory (CGRO) [18] has been used to measure, for two GRBs, the angular distribution of gamma rays back-scattered by the rim of the Earth's atmosphere: $35\% \leq \Pi \leq 100\%$ for GRB930131 and $50\% \leq \Pi \leq 100\%$ for GRB960924. The analysing technique of [17] is only sensitive to the energy range 3-100 keV. Finally, the analysis [19] of GRB041219a across the spectral window 100-350 keV has been performed using coincidence events in the SPI (spectrometer on board of the INTEGRAL satelite [20]) and IBIS (the Imager on Board of the INTEGRAL satelite). The polarization fraction of $\Pi = 96^{+39}_{-40}\%$ was determined for this GRB.

The above mentioned measurements are made using multiple events scattered into a detector with geometry distinguishing capabilities (two adjacent detectors in case of INTEGRAL or rotating detector in case of RHESSI). Because Compton scatter angle depends on the polarization of incoming photons, the time integrated polarization of the prompt gamma ray emission in a GRB can be of the order of tens of per cent provided that the polarization angle does not vary significantly during the whole duration of the GRB across the spectral range analyzed. For example the detected polarization signal in RHESSI arises from a correlation between the time dependence of scattered photon flux and the angular orientation of the satellite, which varies on a time scale similar to the burst duration. The data [21] indicate that a major contribution to the flux comes from photons significantly distributed over at least the energy range 0.2-1.3 MeV.

According to the Hillas [22] [2] diagram showing size and magnetic field strengths of different astrophysical object the typical magnetic field in a GRB's engine can be estimated as $B \simeq 10^9$ G over a region $L_{\rm GRB} \simeq 10^9$ cm. Therefore, one can observe that the constraint arises from the fact that if the axionic dichroism induced angle of polarization rotation (3) in the given magnetic field were to differ by more then $\pi/2$ over the energy range 0.2-1.3 MeV, as in the case of GRB021206, the instantaneous polarization in the detector would fluctuate significantly for the net time averaged polarization of the signal to be suppressed. Similar argument can be applied to the polarization measurements based on INTEGRAL and BATSE events.

To evaluate the bound we assume that in average the magnetic field is sufficiently

[2] See Fig. 10. of [23] for the graphical compilation of [22].

misaligned with the direction of the beam of gamma rays over the magnetized region implying that $\sin 2\phi \simeq 1$ and the axion mass is large enough that for a given energy of gamma rays ω

$$\frac{m_a^2 L_{GRB}}{4\omega} \gtrsim \frac{\pi}{2}. \tag{5}$$

Therefore, the length

$$L_{\rm pass} = \frac{2\pi\omega}{m_a^2} \tag{6}$$

can be interpreted as an analog of the passage length akin to that one which defines the dimension of a magnetized cavity in a laser PVLAS experiment. Thus the number of passages in (3) is given by

$$N = \frac{L_{\rm GRB}}{L_{\rm pass}} \tag{7}$$

and thereby when the condition (5) holds the accumulated polarization rotation angle can be expressed from (3) as

$$\epsilon = \frac{L_{\rm GRB}}{2\pi}\frac{g_{a\gamma\gamma}^2}{m_a^2}\omega B^2. \tag{8}$$

Hence, the relative misalignment between the polarization planes of gamma radiation at two different energies ω_1 and ω_2 is given by

$$\Delta\epsilon = \frac{L_{GRB}}{2\pi}\frac{g_{a\gamma\gamma}^2}{m_a^2}\Delta\omega B^2, \tag{9}$$

where $\Delta\omega = |\omega_2 - \omega_1|$. The statistical pattern of the time integrated polarization signal from a GRB in a detector is preserved for the energy range between ω_1 and ω_2 provided that the relative misalignment angle (9) is less than $\pi/2$. This condition can be transformed into the bound on the axion-photon coupling as

$$g_{a\gamma\gamma} \leq \pi \frac{m_a}{B\sqrt{\Delta\omega L_{\rm GRB}}}. \tag{10}$$

From the last inequality using $B = 1.95 \cdot 10^7$ eV^2 and $\Delta\omega L_{GRB} = 5 \cdot 10^{19}$ for the given magnetic field, energy difference $\Delta\omega = 1$ MeV and the length of magnetized region $L_{GRB} = 10^9$ cm one obtains [3]

$$g_{a\gamma\gamma} \leq 2.2 \cdot 10^{-8} \frac{m_a}{1 \text{ eV}} \text{ (GeV)}^{-1}, \tag{11}$$

where the inner part of the spectral window 0.2-1.3 MeV ($\Delta\omega \approx 1$MeV) reported in polarization analysis of GRB021206 has been used. However, for the axion mass

$$m_a \leq \sqrt{\frac{2\pi\omega}{L_{GRB}}} \tag{12}$$

[3]The values are given in units $c = \hbar = 1$, so that 1T = 195 eV^2 and GeV $\cdot$ cm $= 5 \cdot 10^{13}$.

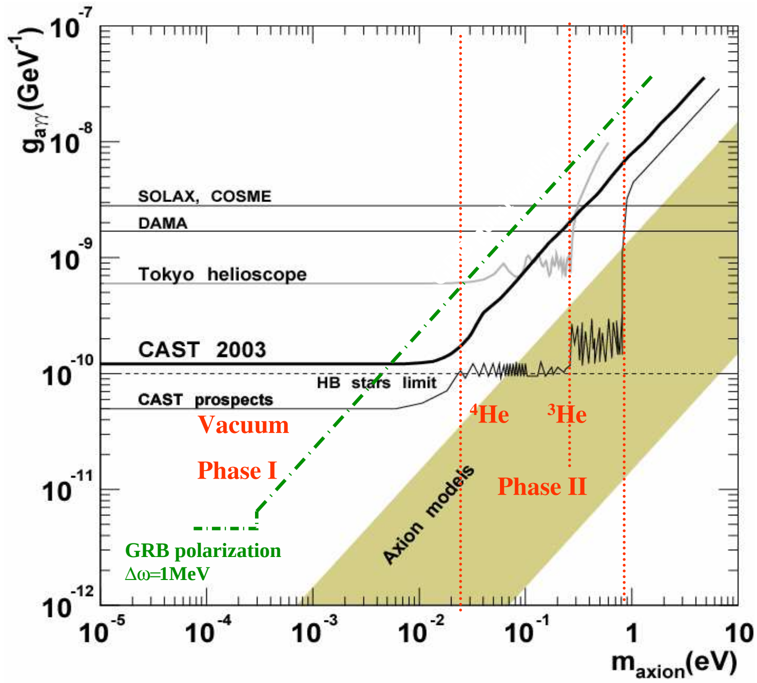

Figure 1: *The plot of the regions of $(m_a, g_{a\gamma\gamma})$ space ruled out by various solar axion searches taken from [4] with the bound of the present letter, estimated for the inner part of the energy range 0.2-1.3 MeV applied for the polarization measurements of GRB021206 (dashed dotted line), superimposed.*

the passage length (6) exceeds L_{GRB} implying that the rotation angle should be expressed as a constant:

$$\epsilon = \frac{g_{a\gamma\gamma}^2}{16}(BL_{\rm GRB})^2. \tag{13}$$

The upper edge $\omega_2 \approx 1.3$ MeV of the energy range considered, together with the condition (12), defines the critical mass

$$m_{cr1} \approx 3.5 \cdot 10^{-4} \text{ eV}. \tag{14}$$

Below this mass the rotation angle of the higher energy photons does not depend either on their energy or the axion mass and is given by (13), while for the lower energy edge of the polarized photons $\omega_1 \approx 0.2$MeV the equation (8) is still valid. Therefore, for the axion mass bellow the critical one, $m_a \leq m_{cr1}$, the polarization planes misalignment angle should be calculated as

$$\Delta\epsilon = B^2 g_{a\gamma\gamma}^2 L_{\rm GRB}\left(\frac{L_{\rm GRB}}{16} - \frac{\omega_1}{2\pi m_a^2}\right). \tag{15}$$

The expression (15) holds to be positive down to the mass

$$m_{\rm cr2} = 4\sqrt{\frac{\omega_1}{2\pi L_{GRB}}} \approx 8\cdot 10^{-5}\ {\rm eV}. \tag{16}$$

Requiring again that the misalignment angle (15) does not exceed $\pi/2$ in the axion mass range between $m_{\rm cr1}$ and $m_{\rm cr2}$ one arrives to a bound, which can be well approximated by a constant

$$g_{a\gamma\gamma} \leq \frac{2\sqrt{2\pi}}{BL_{\rm GRB}} \approx 5\cdot 10^{-12}\ ({\rm GeV})^{-1}. \tag{17}$$

For the masses $m_a \geq 8\cdot 10^{-5}$ eV the rotation of the polarization plane is given by (13) and misalignment does not appear making the bound undefined for the axion mass bellow $m_{\rm cr2}$.

In Fig. 1. we show the bounds (11) and (17) superimposed on the recent results of CAST [24] and other axion helioscope experiments [25, 26, 27, 28, 29]. One can see that the bound obtained from the lack of a substantial misalignment of polarization planes of gamma radiation at different energies within the energy range reported by polarization measurements of GRB021206 is competitive with the current sensitivity of CAST for the axion masses below 10^{-3} eV. Moreover, one observes that it seems to be very unlikely that a laser experiment like PVLAS could find a signal [9] corresponding to $g_{a\gamma\gamma} \simeq 10^{-5}$ GeV^{-1} for the meV axions. Indeed, the lack of the observation of the previously claimed rotation signal [9] has been established recently by the PVLAS team after a substantial upgrade of the facility has been made [10]. Also the PVLAS anomaly has not found a support in the results of a pulsed "light shining through a wall" experiment [30].

Since according to [31] the electron number density in a GRB's environment can be estimated as $n_e \simeq 10^{10}$ cm^{-3} the expression (4) is still axion mass dominated down to $m_a \approx m_{\rm cr}$ for the given magnetic field, the energy of the gamma radiation, $\omega \approx 1$ MeV, and constraints on $g_{a\gamma\gamma}$ calculated from (11) and (17) . Therefore, the validity of the approximation (3) holds in the range of the parameters the bound in Fig.1. is imposed. The minimal time scale of variability of GRBs light curves is estimated to be about 0.1 sec [4]. This implies that the typical extention of the GRB's engine is indeed compatible with $L_{GRB} \approx 10^9$ cm we used for the evaluation of the bound. Conservation of magnetic field energy at the rest wind frame of fireball shell model of the GRB's engine [31] implies at any radial distance r, in the fireball environment, $4\pi r_0^2 B_0^2 = 4\pi r^2 B^2$, leading to the relation $B = B_0(r_0/r)$, where B_0 and r_0 are the magnetic field strength and the size of the central part of the fireball. Typically the central part of the fireball can be represented by a neutron star of radius $r_0 \approx 10^6$ cm with magnetic field of $B_0 \approx 10^{12}$ G. Therefore the strength of the magnetic field at the distance $r = L_{GRB}$ corresponds to $B \approx 10^9$ G, which is in a good agreement with the values taken from [22, 23].

The limit obtained becomes by factor $\sqrt{1{\rm MeV}/\Delta\omega_{I,B}}$ weaker if we apply the width $\Delta\omega_I \approx 250$ keV of the energy bands for GRB041219a detected by INTEGRAL or $\Delta\omega_B \approx$

[4]See, for example, the analysis in [32].

100 keV for GRB930131 and GRB960924 detected by BATSE. This implies that $g_{a\gamma\gamma} \leq 4.4 \cdot 10^{-11}$ GeV^{-1} and $g_{a\gamma\gamma} \leq 6.9 \cdot 10^{-11}$ GeV^{-1} for INTEGRAL and BATSE measurements respectively calculated for the axion mass $m_a = 10^{-3}$ eV. A stronger constraint could be obtained from the GRBs considered by taking into account more precisely the spectral characteristics of the signal and statistical criteria for loosing the polarization pattern in the detectors. Of course, the robustness should find its confirmation in further detection of gamma polarized signals from other GRBs in the similar energy range. In principle, apart from the mentioned instruments SWIFT [33] satellite is also capable of polarimetry [34] in 300 keV-10 MeV energy band.

In recent years, numerous efforts have been initiated to develop instruments with the sensitivity required for astrophysical polarimetry over 100 eV to 10 GeV band [35]. Time projection chambers (TPCs), with their high-resolution event imaging capability, are an integral part of some of this efforts. At the energy band 300 keV-10 MeV, Compton polarimeters based on the use of high-Z scattering elements (coupled with high-Z absorbers) become viable. For example, the Ge double scatter approach used by RHESSI becomes most effective at energies above 300 keV. Liquid rare-gas TPCs are being pursued as large effective area Compton telescopes, while electron-tracking gas TPCs are a component of Compton telescopes with the lowest background, especially for the most polarization sensitive events. In the pair production regime, which is effective in the energy range 2 MeV-10 GeV, only TPCs currently offer the hope [35] of tracking electron-positron pairs or recoil electrons with the accuracy and efficiency required for astronomical polarimetry.

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